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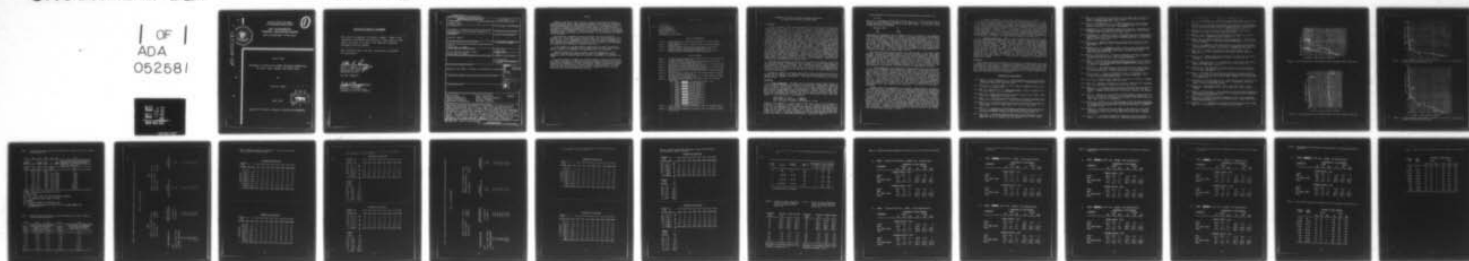
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ESTIMATES OF SATELLITE-TO-EARTH MICROWAVE ATTENUATION BY CLOUD,--ETC(U)
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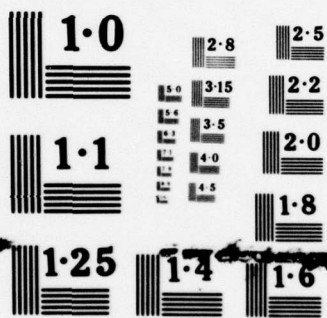
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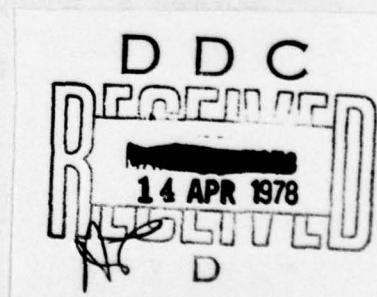
Report 8345

ESTIMATES OF SATELLITE-TO-EARTH MICROWAVE ATTENUATION
BY CLOUD, RAIN, OXYGEN, AND WATER VAPOR

by

Allen R. Davis

April 1977



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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)		
This paper provides estimates of attenuation of space-to-earth radar transmissions due to cloud, rain, and gaseous factors. Attenuation of microwaves of 58-62 GHz and 92-96 GHz are examined. Attenuations through the atmosphere for elevation angles of 50.69° to 90° are calculated and 50, 95, and 99 percentile levels provided. Estimates are based on climatological frequencies of cloud amounts, rain rates, and water vapor, and are provided for two locations: one high-latitude temperate; the other, tropical.		

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Preface

USAFETAC prepared this study to answer a request from Headquarters Rome Air Development Center (RADC). They require estimates of cloud, rain, and atmospheric gaseous attenuation of microwave satellite-to-ground radio transmissions to assist in a feasibility study of a satelliteborne radar system. This report provides estimates of atmospheric attenuation for Central Europe and southern Florida in July and describes the estimating system used. The locations were chosen to represent a reasonable range of conditions. After RADC's evaluation of this system we anticipate processing similar information for other locations. In the future only the results will be provided.

The significant atmospheric factors attenuating radio waves through the atmosphere are cloud, rain, oxygen, and water vapor. The first two factors, cloud and rain, are poorly quantified and require a number of untested hypotheses in their application. If experimental verification of the results is accomplished by RADC, USAFETAC would appreciate being advised of the evaluation so that the models and systems we have used may be validated or modified.

If the requester or any other agency incorporates this report into another report, we request that USAFETAC be given proper credit and be furnished a copy of the new report in all cases where such dissemination is not prohibited.

USAFETAC prepared this report to answer a specific problem and it is not expected to have application beyond that problem. We recommend that further questions on this or related subjects be referred to USAFETAC for consultation and study.

The author wishes to recognize the following people for their contributions to this study. Capt Daniel J. McMorrow directed the computer processing of the data, directed the development of the gaseous attenuation summary, and made many valuable suggestions for improving the study. SSgt James E. Warnke assisted with the data extraction and the processing of computer summaries and calculations. Mr. John Louer, Miss Gertrude K. Holtzmann, Mrs. Esther R. Laumbattus, and Mrs. Carolyn Bertrand edited, formatted, and typed the report.

TABLE OF CONTENTS

Introduction.	Page 1
Discussion.	1
Cloud Attenuation	1
Rain Attenuation.	2
Gaseous Attenuation	2
Combined Attenuation.	3
Conclusion.	3
References and Bibliography	3

LIST OF ILLUSTRATIONS

Figure 1. Cloud Attenuation at 90° Elevation Angle for Central Europe During July.	6
Figure 2. Rain Attenuation at 90° Elevation Angle for Central Europe During July.	6
Figure 3. Combined One-Way Cloud and Rain Attenuation at 60 GHz for Central Europe at 90° Elevation Angle During July.	7
Figure 4. Combined One-Way Cloud and Rain Attenuation at 94 GHz for Central Europe at 90° Elevation Angle During July.	7

LIST OF TABLES

Table 1. One-Way Satellite-to-Earth Cloud Attenuation at 94 GHz (0.32 cm) in Central Europe During July.	8
Table 2. One-Way Satellite-to-Earth Rain Radar Attenuation at 94 GHz (0.32 cm) in Central Europe During July.	8
Table 3. Estimates of One-Way Cloud and Rain Attenuation of 94 and 60 GHz Radio Waves for Central Europe During July	9
Table 4. Estimates of One-Way Cloud and Rain Attenuation of 94 and 60 GHz Radio Waves for Southern Florida During July	12
Table 5. Estimated One-Way Cloud and Rain Attenuation for Central Europe During July.	15
Table 6. One-Way Vertical Attenuation (dB) Due to Water Vapor and Oxygen for Central Europe During July	15
Table 7. One-Way Vertical Attenuation (dB) Due to Water Vapor and Oxygen for Southern Florida During July	15
Table 8. Estimated One-Way Atmospheric Attenuation (dB) for Different Attenuators:	
(a) Angle - 0 , 90° Elevation; Height - All	16
(b) Angle - 0 , 60.68° Elevation; Height - 20,000 Nautical Miles.	16
(c) Angle - 0 , 60.26° Elevation; Height - 10,000 Nautical Miles.	17
(d) Angle - 0 , 59.35° Elevation; Height - 5,000 Nautical Miles	17
(e) Angle - 0 , 58.15° Elevation; Height - 2,000 Nautical Miles	18
(f) Angle - 0 , 56.25° Elevation; Height - 1,000 Nautical Miles	18
(g) Angle - 0 , 54.46° Elevation; Height - 500 Nautical Miles	19
(h) Angle - 0 , 52.09° Elevation; Height - 200 Nautical Miles	19
(i) Angle - 0 , 50.69° Elevation; Height - 100 Nautical Miles	20
Table 9. Total One-Way Atmospheric Attenuation (dB) for Central Europe During July.	20
Table 10. Total One-Way Atmospheric Attenuation (dB) for Southern Florida During July.	21

ESTIMATES OF SATELLITE-TO-EARTH MICROWAVE ATTENUATION BY CLOUD, RAIN, OXYGEN, AND WATER VAPOR

Introduction

Current knowledge of cloud and rain parameters that influence the attenuation of radio waves in the regions 58 to 62 GHz and 92 to 96 GHz consists of a very few research-type observations of the necessary elements. Conventional climatological technique under these circumstances is to relate the few available observations to routinely-observed elements with the intention of developing distributions or probability levels of the desired parameters. Cloud attenuation of microwave transmissions is a function of cloud temperature, phase, liquid-water content (LWC), and cloud-size distributions. The cloud phase is treated by assuming that all cloud particles are liquid at temperatures above -3.5°C and frozen below that temperature. Dudzinsky [14] states that "the attenuation of snow and hail is expected to be much less than that produced by equivalent rainfall." Other authors indicate it to be as much as two orders of magnitude less. Therefore, for our estimates we may confine our area of analysis to levels below the -3.5°C height. This analysis assumes the LWC in clouds (with very little objective justification) to be correlated to the cloud amount; higher LWCs are associated with overcast clouds. Cloud thickness is arbitrarily related to cloud amount and is used in relating the space-size cloud distribution to the path length through clouds. A simplified two-dimensional modeling technique performs this function. Factors relating cloud thickness to cloud amount are also arrived at subjectively. Because of the lack of climatological observations of these cloud properties a more sophisticated system for calculating cloud attenuation is not considered justified. Cloud attenuation is probably the weakest part of the system we are using to derive total attenuation. Lack of a reliable data base precludes more accurate estimates.

Precipitation attenuation is related to the average precipitation (rain) rate over the path length. Precipitation is also assumed to be in the liquid form only from the surface to the -3.5°C height. The rain-rate distribution is also assumed to be constant from the surface to this level. The system used for obtaining rain attenuation is more reliable than the one used to find the cloud attenuation because of the availability of better rain-rate data and because the models used have been tested with good results.

Estimates of gaseous attenuation distributions have been derived using the system described by O'Brien [31]. These estimates are considered reliable. All attenuations are for one-way transmissions. They should be doubled if one requires two-way values.

Discussion

a. Cloud Attenuation. The model used in obtaining frequency distributions of cloud attenuation depends on frequencies of low and middle cloud amount. Summaries of this parameter are available or may be derived for many stations world-wide. The model is divided into two parts. The first part provides frequencies. The second part provides the corresponding cloud attenuations. Observed low- and middle-cloud amounts may be summarized to obtain distributions of eighths (octas) of sky cover. This cloud attenuation model assumes that water clouds are confined to the layer between the mean height of the cloud base and the mean height of the -3.5°C temperature. In Central Europe in July these are:

Mean height of -3.5°C	= 4.816 km
Mean height of cloud base	= 1.829 km
Mean cloud layer thickness	= 2.987 (approx. 3.0 km)

Frequency distributions of cloud amounts below 4.816 km are first obtained as illustrated in Table 1, columns 1 and 2. If, for example, 3/8 sky cover is occurring, the probability of a vertical beam passing through clouds would be 3/8 or 0.375. If this 3/8 cloud cover occurs 9.2% of the time the beam would pass through cloud when this amount is occurring $0.375 \times 0.092 = 0.035$, or 3.5% of the time. Frequencies of other sky cover increments are similarly computed and presented in column 3 of Table 1. Cumulative frequencies of cloud amount cumulating from high- to low-cloud amount are calculated and presented in column 4 of Table 1.

Cloud attenuation is calculated using the following equation from Benoit [4]:

$$A_c = K\rho r$$

where A_c is attenuation through the cloud in dB, K is a constant whose value is related to the frequency of transmission and temperature, r is the path length through the cloud in kilometers, and ρ is the LWC in gm/m³. The value of K at 0°C is determined from the following:

Frequency (GHz)	K
60	3.07
94	7.38

Attenuation is calculated using the assumed LWC (col. 5) of Table 1, and assuming a cloud-thickness coefficient (col. 6) equal to the particular sky-cover increment, i.e., 1/8 sky cover is assigned a (1/8) 0.125 thickness coefficient. Thus, if the cloud layer thickness is 3 km, the 1/8 sky-cover clouds are assumed to be 3 km X 0.125 or 0.375 km thick. Liquid-water content (LWC) is assigned in column 5. Knowing the LWC, ray wavelength, and path in clouds, and assuming a temperature of 0°C, we calculate the attenuation through the cloud increment. For 1/8 cloud cover, 0.59 dB, we now have the cumulative frequency and corresponding one-way cloud attenuation. Columns 4 and 7 of Table 1 present this information for 90° elevation angle and 94 GHz (0.32 cm). In this particular case the cloud attenuation/frequency distribution is the same to all levels (above 4.816 km).

Note that cloud-layer thickness refers to the entire layer in which water clouds may occur, while cloud thickness refers to the cloud thickness of each cloud amount category. Assigning a thickness coefficient which relates thickness to cloud amount (thought to be reasonable) conveniently solves much of the geometry of the problem, such as when going from a vertical to a horizontal (or any in between) ray path. This assumption may be interpreted to indicate that all clouds for each increment are grouped into one elliptical spheroid whose vertical axis, for example, for 3/8 cloud cover, is 3/8 of the cloud-layer thickness, 3/8 X 3 km or 1.125 km, and whose horizontal axis is 3/8 of the horizontal ray path with the ray path limited to the same magnitude as the diameter of sky dome observed, or approximately 100 miles.

b. Rain Attenuation. The calculation of rain attenuation is more direct although it, too, requires several simplifying assumptions. As mentioned previously, the rain rate is considered constant from the surface to the -3.5°C level (4.8 km in Central Europe in July). Frequencies of rain rates come from recorded data in this case. Bussey [6] hypothesized and offered some proof, which has been validated by studies at USAFETAC and by other investigators, to the effect that: distributions of rain rates at a point are similar to distributions of average instantaneous rain rates over some distance, and further, that distributions of point rain rates measured over 1-hour intervals are similar to distributions of average instantaneous rain rates measured over distances on the order of 50 km, while distributions of rain rates measured over 1-minute intervals are similar to distributions of average instantaneous rain rates measured over distances on the order of a few (<10) kilometers.

USAFETAC applied this hypothesis to this problem. Distributions of "clock-hour" rain rates have been transformed using the system described by Davis and McMorrow [10] into distributions of 1-minute rates. Using Bussey's hypothesis we applied the 1-minute rain-rate distributions to rain paths less than 10 km, and the "clock-hour" rain-rate distributions to rain paths of 30 to 50 km. Attenuation rates corresponding to rain-rate thresholds for each frequency came from Medhurst [30]. Table 2 illustrates the computation of the frequency distributions of rain attenuation. Frequencies of the rain rates indicated in column 8 are tabulated in "clock-hour" and "1-minute" intervals in columns 9 and 10. Corresponding attenuation rates from Medhurst [30] appear in column 11 and one-way attenuation over the specified path length (surface to -3.5°C) is calculated (path length times attenuation rate) and listed in column 12. We now have two frequency columns (9 and 10) and one attenuation column (12). Depending on the path length (if less than 10 km, we use frequencies in column 10, if near 50 km, column 9) and can construct graphs of rain attenuation as illustrated in Figures 1 through 4.

c. Gaseous Attenuation. Water vapor and oxygen are the principal gaseous attenuators of radio transmissions in the 58 to 62 and 92 to 96 GHz bands. Oxygen is an especially strong attenuator in and near the 61 GHz band region. The oxygen content of the atmosphere varies only slightly so that oxygen attenuation at the 1%, 5%, and 50% levels are essentially the same. Water vapor attenuates far less than oxygen, but does vary for the percentile levels. The result is that the combined gaseous attenuation varies by only a few tenths of a decibel from the 1- to 50-percentile levels. Tables 6 and 7 indicate the vertical (90° elevation angle) one-way attenuation for the three percentile levels. These are based on a mean July vertical atmospheric profile for the location and the specified percentile level of the surface LWC. Attenuation for other elevation angles is obtained by multiplying by the cosecant of the angle. The system used is described by O'Brien [31].

d. Combined Attenuation. Tables 3 and 4 contain information on the input values and the results of computations for both wavelengths and satellite height/elevation angles for rain and cloud separately. Table 5 summarizes the combined rain and cloud attenuation frequencies for three percentile levels for four representative elevation angles. Computer tables of oxygen and water-vapor attenuation have been provided separately. Tables 8a through 8i list the three percentile values (1%, 5%, and 50%) of cloud, rain, and oxygen plus water vapor and also provide estimates of totals based on the assumption that these values are highly correlated. That is, heavy rain, dense clouds, and high values of water vapor occur simultaneously. Finally, total atmospheric attenuation, one way, through the atmosphere from all heights perpendicular to the earth's surface (90° elevation angle) and from each height to one-half the nadir to earth tangent angle are presented in Tables 9 and 10. In these tables, attenuation is rounded to the nearest whole decibel.

Conclusion

This report explains the methods of calculation and hypothesis used in arriving at certain percentile levels of atmospheric attenuation of millimeter-band radio transmissions. Attenuations are calculated separately for clouds, rain, oxygen, and water vapor, and then combined. Several of the key hypotheses used have very little or no objective justification and are based only on the author's opinion. For this reason the results obtained should be considered only as very general approximations of the values likely to be encountered.

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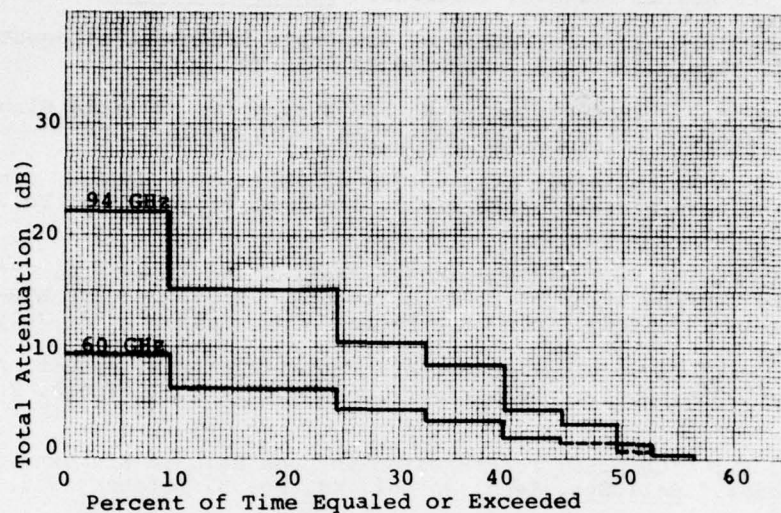


Figure 1. Cloud Attenuation at 90° Elevation Angle for Central Europe During July.

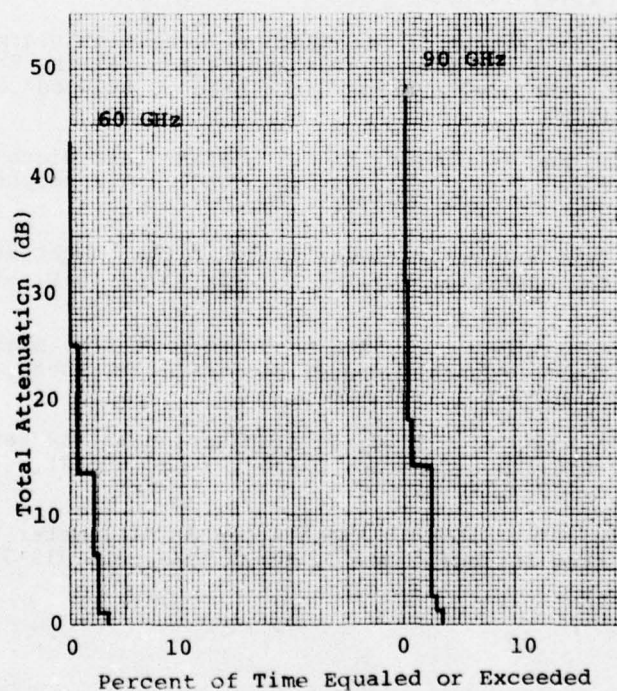


Figure 2. Rain Attenuation at 90° Elevation Angle for Central Europe During July.

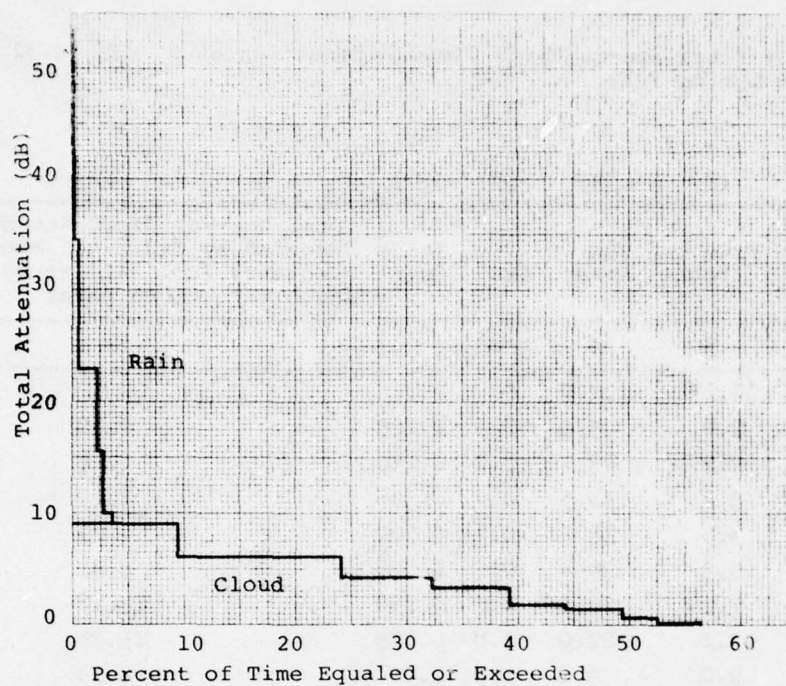


Figure 3. Combined One-Way Cloud and Rain Attenuation at 60 GHz for Central Europe at 90° Elevation Angle During July.

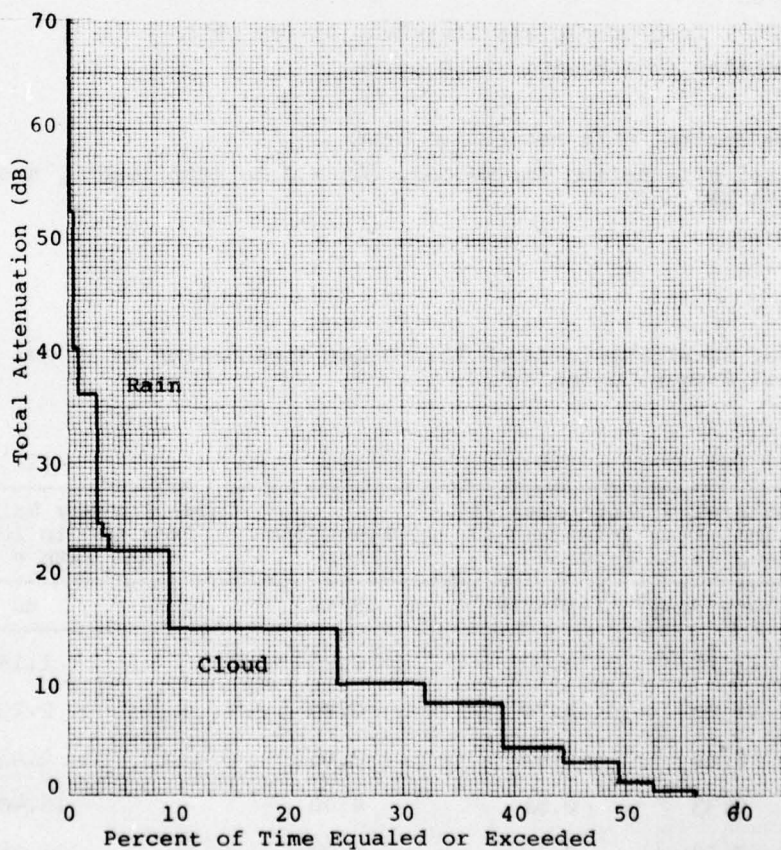


Figure 4. Combined One-Way Cloud and Rain Attenuation at 94 GHz for Central Europe at 90° Elevation Angle During July.

Table 1. One-Way Satellite-to-Earth Cloud Attenuation at 94 GHz (0.32 cm) in Central Europe During July.

(1)	(2)	(3)	(4)	(5)	(6)	(7)
Low/Mid Cld Amt	Freq	Freq on Path	Cum Freq	LWC	Thick Coef	Total One-Way Cloud Attenuation (dB) Exceeded by Indicated Percentage Frequency [col (4)] at 90° Elevation Angle thru Cloud Layer
Octas	%	%	%	g/m ³		dB
0	15.4	54.1*	100.0	0	0	0
1	17.7	2.2	45.9	0.2	0.125	0.59
2	8.7	2.2	43.7	0.2	0.250	1.18
3	9.2	3.5	41.5	0.4	0.375	3.25
4	7.1	3.6	38.0	0.4	0.500	4.43
5	8.5	5.3	34.4	0.6	0.625	8.41
6	9.5	7.1	29.1	0.6	0.750	10.18
7	14.9	13.1	22.0	0.8	0.875	15.35
8	9.0	9.0	9.0	1.0	1.00	22.14

* 100% - (sum of sky cover freq 0.1 to 1.0)

(2) from records

(3) = (1) x (2) = freq of cld amt increment on ray path

(4) = (3) cumulated from 8 octas to 0 octas

(5) assumed

(6) = assigned decimal = to respective octa

(7) = calculated attenuation for 94 GHz, (6) x 3 km path length, and specified LWC

Table 2. One-Way Satellite-to-Earth Rain Radar Attenuation at 94 GHz (0.32cm) in Central Europe During July.

(8)	(9)	(10)	(11)	(12)
Precip. Rate	% Time Precip. Rate Measured Over Indicated Intervals is Equalled or Exceeded	Rate Measured is	Attenuation Rate	Total One-Way Rain Attenuation Over 90° to 100 NM Path Slant Path = 4.60 km
mm/hr	"Clock Hour"	1-Minute	dB/km	dB
0.25	13.18	3.50	0.25	1.15
0.51	11.66	2.70	0.49	2.25
2.54	2.52	2.49	2.05	9.43
6.35	0.33	0.61	4.00	18.40
12.70	0.03	0.19	6.80	31.28
25.40	0.00	0.04	11.70	53.82

Table 3. Estimates of One-Way Cloud and Rain Attenuation of 94 and 60 GHz Radio Waves for Central Europe During July.

Table 3a. Ray-Path Geometry

	<u>CLOUD</u>		<u>RAIN</u>	
	Height of -3.5°C Surface = 4.816 km	Height of -3.5°C Surface = 4.816 km	Height of -3.5°C Surface = 4.816 km	Height of -3.5°C Surface = 4.816 km
	Height of Cloud Base = 1.829 km	Height of Cloud Base = 1.829 km	Height of Ground Surface = 0.2 km	Height of Ground Surface = 0.2 km
	Cloud Thickness = 2.987 km	Cloud Thickness = 2.987 km	Rain Thickness = 4.616 km	Rain Thickness = 4.616 km
Angles WRT Nadir (NM)	Elevation Angle at Earth's Surface (deg)		Slant Path through Cloud Layer (km)	
	All Heights 90°		Slant Path through Rain (km)	
Nadir	All Heights 90°		4.6	
Tangent to Earth's Surface	All Heights 0°		276	
1/2 Tangent to Nadir (NM)				
TO:				
100	50.69	3.9	6.0	
200	52.09	3.8	5.9	
500	54.46	3.7	5.7	
1000	56.25	3.6	5.6	
2000	58.15	3.5	5.4	
5000	59.35	3.5	5.4	
10,000	60.26	3.5	5.3	
22,000	60.68	3.4	5.3	

Table 3b. Estimate of One-Way Cloud Attenuation. Percent of Time Indicated Cloud Attenuation is Equaled or Exceeded.

Attenuation at 94 GHz (dB)										
Elevation Angle	90°	0°	50.69°	52.09°	54.46°	56.25°	58.15°	59.35°	60.26°	60.68°
Hts (NM)	ALL	ALL	100	200	500	1000	2000	5000	10,000	22,000
100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
P F 45.9	0.6	42.1	0.7	0.7	0.7	0.7	0.6	0.6	0.6	0.6
E R 43.7	1.2	84.1	1.5	1.5	1.3	1.3	1.3	1.3	1.3	1.3
R E 41.5	3.2	252.4	4.4	4.1	4.1	4.1	3.8	3.8	3.8	3.8
C Q 38.0	4.4	336.5	5.9	5.6	5.6	5.3	5.3	5.3	5.3	5.0
E U 34.4	8.4	631.0	10.6	10.6	10.2	10.2	9.7	9.7	9.7	9.3
N E 29.1	10.2	757.2	12.8	12.8	12.4	12.0	11.5	11.5	11.5	11.5
T N 22.0	15.4	1177.8	20.1	19.5	18.9	18.9	18.3	18.3	18.3	17.7
C Y 9.0	22.1	1682.6	28.8	28.0	27.3	26.6	25.8	25.8	25.8	25.1

Attenuation at 60 GHz (dB)										
Elevation Angle	90°	0°	50.69°	52.09°	54.46°	56.25°	58.15°	59.35°	60.26°	60.68°
Hts (NM)	ALL	ALL	100	200	500	1000	2000	5000	10,000	22,000
100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
P F 45.9	0.2	17.5	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2
E R 43.7	0.5	35.0	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
R E 41.5	1.4	105.0	1.8	1.7	1.7	1.7	1.6	1.6	1.6	1.6
C Q 38.0	1.8	140.0	2.5	2.3	2.3	2.2	2.2	2.2	2.2	2.1
E U 34.4	3.5	262.5	4.4	4.4	4.2	4.2	4.1	4.1	4.1	3.9
N E 29.1	4.2	315.0	5.3	5.3	5.2	5.0	4.8	4.8	4.8	4.8
T N 22.0	6.4	490.0	8.4	8.1	7.9	7.9	7.6	7.6	7.6	7.4
C Y 9.0	9.2	700.0	12.0	11.7	11.4	11.1	10.7	10.7	10.7	10.4

Table 3c. Estimate of One-Way Rain Attenuation. Percent of Time Indicated Rain Attenuation is Equalled or Exceeded.

Attenuation at 94 GHz (dB)										
Elevation Angle	90°		50.69°	52.09°	54.46°	56.25°	58.15°	59.35°	60.26°	60.68°
Hts (NM)	ALL		100	200	500	1000	2000	5000	10,000	22,000
P F	3.50	1.2	↓	1.5	1.5	1.4	1.4	1.4	1.4	1.3
E R	2.70	2.3	↓	2.9	2.9	2.8	2.7	2.6	2.6	2.6
R E	2.49	9.4	↓	12.3	12.1	11.7	11.5	11.1	10.9	10.9
C Q	0.61	18.4	↓	24.0	23.6	22.8	22.4	21.6	21.2	21.2
E U	0.19	31.3	↓	40.8	40.1	38.8	38.1	36.7	36.0	36.0
T N	0.04	53.8	↓	70.2	69.0	66.7	65.5	63.2	62.0	62.0
C										
Y										
Elevation Angle	0°									
Hts (NM)	ALL									
P F	13.18	69.0								
E R	11.66	135.3								
R E	2.42	566.0								
C Q	0.33	1104.4								
E U	0.03	1877.5								
T N	0.00	3230.0								
C										
Y										

Attenuation at 60 GHz (dB)										
Elevation Angle	90°		50.69°	52.09°	54.46°	56.25°	58.15°	59.35°	60.26°	60.68°
Hts (NM)	ALL		100	200	500	1000	2000	5000	10,000	22,000
P F	3.50	0.7	↓	0.9	0.9	0.9	0.8	0.8	0.8	0.8
E R	2.70	1.4	↓	1.9	1.8	1.8	1.7	1.7	1.6	1.6
R E	2.49	6.3	↓	8.2	8.0	7.8	7.6	7.3	7.2	7.2
C Q	0.61	13.8	↓	18.0	17.7	17.1	16.8	16.2	15.9	15.9
E U	0.19	25.3	↓	33.0	32.5	31.4	30.8	29.7	29.2	29.2
T N	0.04	43.7	↓	57.0	56.1	54.2	53.2	51.3	50.4	50.4
C										
Y										
Elevation Angle	0°									
Hts (NM)	ALL									
P F	13.18	41.4								
E R	11.66	85.6								
R E	2.42	375.5								
C Q	0.33	828.3								
E U	0.03	1518.6								
T N	0.00	2623.0								
C										
Y										

Table 4. Estimates of One-Way Cloud and Rain Attenuation of 94 and 60 GHz Radio Waves for Southern Florida During July.

Table 4a. Ray-Path Geometry.

Height of -3.5°C Surface = 17,760 ft	Height of -3.5°C Surface = 17,760 ft
Height of Cloud Base = 3,000 ft	Height of Ground Surface = 0 ft
Cloud Thickness 14,760 ft	Rain Thickness 17,760 ft

Angles WRT Nadir (NM)	Elevation Angle at Earth's Surface (deg)	Slant Path through Cloud Layer (km)	Slant Path through Rain (km)
Nadir	All Heights 90°	4.5	5.4
Tangent to Earth's Surface	All Heights 0°	259.5	297
1/2 Tangent to Nadir (NM)			
TO: 100	50.69	5.8	7.0
200	52.09	5.7	6.8
500	54.46	5.5	6.6
1000	56.25	5.4	6.5
2000	58.15	5.3	6.4
5000	59.35	5.2	6.3
10,000	60.26	5.2	6.2
22,000	60.68	5.2	6.2

Table 4b. Estimate of One-Way Cloud Attenuation. Percent of Time Indicated Cloud Attenuation is Equalled or Exceeded.

		Attenuation at 94 GHz (dB)									
Elevation Angle		90°	0°	50.69°	52.09°	54.46°	56.25°	58.15°	59.35°	60.26°	60.68°
Hts (NM)		ALL	ALL	100	200	500	1000	2000	5000	10,000	22,000
	100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
P F	19.2	0.9	47.8	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
E R	18.9	1.6	95.8	2.2	2.1	2.1	2.1	1.9	1.9	1.9	1.9
R E	17.6	5.0	287.2	6.5	6.2	6.2	5.9	5.9	5.9	5.9	5.9
C Q	15.9	6.8	383.2	8.6	8.6	8.3	8.0	8.0	7.7	7.7	7.7
E U	13.1	12.4	718.2	15.9	15.9	15.1	15.1	14.6	14.6	14.6	14.6
N E	10.3	15.1	861.7	19.5	19.0	18.2	18.2	17.7	17.3	17.3	17.3
T N	5.4	23.0	1340.8	30.1	29.5	28.3	27.7	27.2	27.2	27.2	27.2
C Y	3.3	33.2	1915.1	42.8	42.1	40.6	39.9	39.1	38.4	38.4	38.4

		Attenuation at 60 GHz (dB)									
Elevation Angle		90°	0°	50.69°	52.09°	54.46°	56.25°	58.15°	59.35°	60.26°	60.68°
Hts (NM)		ALL	ALL	100	200	500	1000	2000	5000	10,000	22,000
	100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
P F	19.2	0.4	19.9	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
E R	18.9	0.7	39.8	0.9	0.9	0.9	0.9	0.8	0.8	0.8	0.8
R E	17.6	2.1	119.5	2.7	2.6	2.6	2.5	2.5	2.5	2.5	2.5
C Q	15.9	2.8	159.4	3.6	3.6	3.4	3.3	3.2	3.2	3.2	3.2
E U	13.1	5.2	298.8	6.6	6.6	6.3	6.3	6.1	6.1	6.1	6.1
N E	10.3	6.3	358.5	8.1	7.9	7.6	7.6	7.2	7.2	7.2	7.2
T N	5.4	9.6	557.8	12.5	12.3	11.8	11.5	11.3	11.3	11.3	11.3
C Y	3.3	13.8	796.7	17.8	17.5	16.9	16.6	16.3	16.0	16.0	16.0

Table 4c. Estimate of One-Way Rain Attenuation. Percent of Time Indicated Rain Attenuation is Equaled or Exceeded.

Attenuation at 94 GHz (dB)										
Elevation Angle	90°	50.69°	52.09°	54.46°	56.25°	58.15°	59.35°	60.26°	60.68°	
Hts (NM)	ALL	100	200	500	1000	2000	5000	10,000	22,000	
P F	3.17	1.4	↓	1.8	1.7	1.7	1.6	1.6	1.6	1.6
E R	2.58	2.6	↓	3.4	3.3	3.2	3.2	3.1	3.1	3.0
C Q	1.27	11.1	↓	14.4	13.9	13.5	13.3	13.1	12.9	12.7
E U	0.60	21.6	↓	28.0	27.2	26.4	26.0	25.6	25.2	24.8
N E	0.32	36.7	↓	47.6	46.2	44.9	44.2	43.5	42.8	42.2
T N	0.19	63.2	↓	81.9	79.6	77.2	76.1	74.9	73.7	72.5
C										
Y										
Elevation Angle 0°										
Hts (NM)	ALL									
P F	5.4	74.3								
E R	4.2	145.5								
C Q	1.9	608.9								
E U	0.9	1188.0								
N E	0.4	2019.6								
T N	0.1	3474.9								
C										
Y										

Attenuation at 60 GHz (dB)										
Elevation Angle	90°	50.69°	52.09°	54.46°	56.25°	58.15°	59.35°	60.26°	60.68°	
Hts (NM)	ALL	100	200	500	1000	2000	5000	10,000	22,000	
P F	3.17	0.8	↓	1.1	1.0	1.0	1.0	0.9	0.9	0.9
E R	2.58	1.7	↓	2.2	2.1	2.0	2.0	2.0	1.9	1.9
C Q	1.27	7.3	↓	9.5	9.4	9.0	8.8	8.7	8.6	8.4
E U	0.60	16.2	↓	21.0	20.4	19.8	19.5	19.2	18.9	18.6
N E	0.32	29.7	↓	38.5	37.4	36.3	35.8	35.2	34.7	34.1
T N	0.19	51.3	↓	66.5	64.6	62.7	61.8	60.8	59.9	58.9
C										
Y										
Elevation Angle 0°										
Hts (NM)	ALL									
P F	5.4	44.5								
E R	4.2	92.1								
C Q	1.9	403.9								
E U	0.9	891.0								
N E	0.4	1633.5								
T N	0.1	2821.5								
C										
Y										

Table 5. Estimated One-Way Cloud and Rain Attenuation for Central Europe During July.

Nadir Angle	Height	Elevation Angle	Frequency GHz	Percentage of Time Indicated Attenuation (dB) Exceeded		
				50%	5%	1%
0°	ALL	90°	94	1	27	36
			60	1	9	35
*	200 NM	52.09°	94	2	28	52
			60	1	12	20
*	1000 NM	56.25°	94	2	27	39
			60	1	11	19
*	20,000 NM	60.68°	94	1	25	36
			60	1	10	18

* $\frac{1}{2}$ between nadir and tangent

Table 6. One-Way Vertical Attenuation (dB)* Due to Water Vapor and Oxygen for Central Europe During July.

Frequency (GHz)	Percent of Time Exceeded		
	50	5	1
58	99.3	99.4	99.5
59	131.3	131.4	131.5
60	124.7	124.8	124.9
61	136.5	136.4	136.5
62	120.3	120.4	120.5
92	1.0	1.3	1.4
93	1.0	1.3	1.4
94	1.0	1.3	1.4
95	1.0	1.3	1.4
96	1.0	1.3	1.5

Calculated to 30 km above station level.

* Rounded to nearest 0.1 dB.

Table 7. One-Way Vertical Attenuation (dB)* Due to Water Vapor and Oxygen for Southern Florida During July.

Frequency (GHz)	Percent of Time Exceeded		
	50	5	1
58	98.7	98.8	98.9
59	131.6	141.6	131.6
60	123.8	123.8	123.9
61	136.6	136.6	136.7
62	120.2	120.3	120.3
92	1.7	1.8	1.8
93	1.7	1.8	1.8
94	1.7	1.8	1.9
95	1.7	1.8	1.9
96	1.7	1.9	1.9

Calculated to 30 km above station level.

* Rounded to nearest 0.1 dB.

Table 8. Estimated One-Way Atmospheric Attenuation (dB) for Different Attenuators.

(a) ANGLE: 0° nadir; 90° elevation. HEIGHT: All - nautical miles.

ATTENUATOR	PERCENTAGE OF TIME EXCEEDED					
	94 GHz			60 GHz		
	1%	5%	50%	1%	5%	50%
CENTRAL EUROPE - JULY						
Cloud	22.1	22.1	0	9.2	9.2	0
Rain	31.3	0	0	25.3	0	0
O ₂ + Water Vapor	1.4	1.3	1.0	124.9	124.8	124.7
Total	54.8	23.4	1.0	159.4	134.0	124.7
SOUTHERN FLORIDA - JULY						
Cloud	33.2	23.0	0	13.8	9.6	0
Rain	11.1	0	0	7.3	0	0
O ₂ + Water Vapor	1.9	1.8	1.7	123.9	123.8	123.8
Total	46.2	24.8	1.7	145.0	133.4	123.8

(b) ANGLE: 0° nadir; 60.68° elev. HEIGHT: 20,000 nautical miles.

ATTENUATOR	PERCENTAGE OF TIME EXCEEDED					
	94 GHz			60 GHz		
	1%	5%	50%	1%	5%	50%
CENTRAL EUROPE - JULY						
Cloud	25.3	25.3	0	10.5	10.5	0
Rain	35.8	0	0	29.0	0	0
O ₂ + Water Vapor	1.6	1.4	1.1	143.2	143.1	143.0
Total	62.7	26.8	1.1	182.8	153.6	143.0
SOUTHERN FLORIDA - JULY						
Cloud	38.0	26.3	0	15.8	11.0	0
Rain	12.7	0	0	8.3	0	0
O ₂ + Water Vapor	2.1	2.0	1.9	142.1	141.9	141.9
Total	52.9	28.4	1.9	166.3	152.9	141.9

Table 2. Estimated One-Way Atmospheric Attenuation (dB) for Different Attenuators (Continued).

(c) ANGLE: ~~██████~~; 60.26° elev. HEIGHT: 10,000 nautical miles.

ATTENUATOR	PERCENTAGE OF TIME EXCEEDED					
	94 GHz			60 GHz		
	1%	5%	50%	1%	5%	50%
CENTRAL EUROPE - JULY						
Cloud	25.4	25.4	0	10.5	10.5	0
Rain	36.0	0	0	29.1	0	0
O ₂ + Water Vapor	1.6	1.4	1.1	143.8	143.7	143.6
Total	63.1	26.9	1.1	183.5	154.3	143.6
SOUTHERN FLORIDA - JULY						
Cloud	38.2	26.4	0	15.8	11.0	0
Rain	12.7	0	0	8.4	0	0
O ₂ + Water Vapor	2.1	2.0	1.9	142.6	142.5	142.5
Total	53.2	28.5	1.9	166.9	153.6	142.5

(d) ANGLE: ~~██████~~; 59.35° elev. HEIGHT: 5000 nautical miles.

ATTENUATOR	PERCENTAGE OF TIME EXCEEDED					
	94 GHz			60 GHz		
	1%	5%	50%	1%	5%	50%
CENTRAL EUROPE - JULY						
Cloud	25.6	25.6	0	10.6	10.6	0
Rain	36.3	0	0	29.4	0	0
O ₂ + Water Vapor	1.6	1.5	1.1	145.1	145.0	144.9
Total	63.6	27.1	1.1	185.2	155.7	144.9
SOUTHERN FLORIDA - JULY						
Cloud	38.5	26.7	0	16.0	11.1	0
Rain	12.9	0	0	8.5	0	0
O ₂ + Water Vapor	2.2	2.0	1.9	144.0	143.9	143.9
Total	53.7	28.8	1.9	168.5	155.0	143.9

Table 8. Estimated One-Way Atmospheric Attenuation (dB) for Different Attenuators (Continued).

(e) ANGLE: ~~58.15°~~; 58.15° elev. HEIGHT: 2000 nautical miles.

ATTENUATOR	PERCENTAGE OF TIME EXCEEDED					
	94 GHz			60 GHz		
	1%	5%	50%	1%	5%	50%
CENTRAL EUROPE - JULY						
Cloud	26.0	26.0	0	10.8	10.8	0
Rain	36.8	0	0	29.7	0	0
O ₂ + Water Vapor	1.6	1.5	1.1	147.0	146.9	146.8
Total	64.5	27.5	1.1	187.6	157.7	146.8
SOUTHERN FLORIDA - JULY						
Cloud	39.0	27.6	0	16.2	11.3	0
Rain	13.0	0	0	8.5	0	0
O ₂ + Water Vapor	2.2	2.1	2.0	145.8	145.7	145.8
Total	54.3	29.1	2.0	170.7	157.0	145.8

(f) ANGLE: ~~56.25°~~; 56.25° elev. HEIGHT: 1000 nautical miles.

ATTENUATOR	PERCENTAGE OF TIME EXCEEDED					
	94 GHz			60 GHz		
	1%	5%	50%	1%	5%	50%
CENTRAL EUROPE - JULY						
Cloud	26.5	26.5	0	11.0	11.0	0
Rain	37.6	0	0	30.4	0	0
O ₂ + Water Vapor	1.6	1.5	1.2	150.2	150.0	149.9
Total	65.9	28.1	1.2	191.7	161.1	149.9
SOUTHERN FLORIDA - JULY						
Cloud	39.9	27.6	0	16.5	11.5	0
Rain	13.3	0	0	8.7	0	0
O ₂ + Water Vapor	2.2	2.1	2.0	149.0	148.8	148.8
Total	55.5	29.8	2.0	174.3	160.4	148.8

Table 8. Estimated One-Way Atmospheric Attenuation (dB) for Different Attenuators (Continued).

(g) ANGLE: ~~50.46°~~; 54.46° elev. HEIGHT: 500 nautical miles.

ATTENUATOR	PERCENTAGES OF TIME EXCEEDED					
	94 GHz			60 GHz		
	1%	5%	50%	1%	5%	50%
CENTRAL EUROPE - JULY						
Cloud	27.1	27.1	0	11.3	11.3	0
Rain	38.4	0	0	31.0	0	0
O ₂ + Water Vapor	1.7	1.5	1.2	153.4	153.3	153.2
Total	67.3	28.7	1.2	195.8	164.6	153.2

SOUTHERN FLORIDA - JULY						
Cloud	40.8	28.2	0	16.9	11.7	0
Rain	13.6	0	0	8.9	0	0
O ₂ + Water Vapor	2.3	2.2	2.0	152.2	152.1	152.1
Total	56.7	30.4	2.0	178.1	163.9	152.1

(h) ANGLE: ~~50.46°~~; 52.09° elev. HEIGHT: 200 nautical miles.

ATTENUATOR	PERCENTAGES OF TIME EXCEEDED					
	94 GHz			60 GHz		
	1%	5%	50%	1%	5%	50%
CENTRAL EUROPE - JULY						
Cloud	28.0	28.0	0	11.6	11.6	0
Rain	39.6	0	0	32.0	0	0
O ₂ + Water Vapor	1.7	1.6	1.2	158.3	158.1	158.0
Total	69.4	29.6	1.2	202.0	169.8	158.0

SOUTHERN FLORIDA - JULY						
Cloud	42.0	29.1	0	17.4	12.1	0
Rain	14.0	0	0	9.2	0	0
O ₂ + Water Vapor	2.4	2.2	2.1	157.0	156.9	156.9
Total	58.5	31.4	2.1	183.7	169.0	156.9

Table 8. Estimated One-Way Atmospheric Attenuation (dB) for Different Attenuators (Continued).

(i) ANGLE: ~~90°~~; 50.69° elev. HEIGHT: 100 nautical miles.

ATTENUATOR	PERCENTAGES OF TIME EXCEEDED					
	94 GHz			60 GHz		
	1%	5%	50%	1%	5%	50%
CENTRAL EUROPE - JULY						
Cloud	28.5	28.5	0	11.8	11.8	0
Rain	40.5	0	0	32.7	0	0
O ₂ + Water Vapor	1.8	1.7	1.2	161.4	161.3	161.2
Total	70.8	30.2	1.2	198.5	173.1	161.2
SOUTHERN FLORIDA - JULY						
Cloud	42.9	29.7	0	17.8	12.4	0
Rain	14.3	0	0	9.4	0	0
O ₂ + Water Vapor	2.5	2.3	2.2	160.1	160.0	160.0
Total	59.7	32.0	2.2	187.3	172.4	160.0

Table 9. Total One-Way Atmospheric Attenuation (dB) for Central Europe During July.

HEIGHTS NM	ELEV ANGLE	PERCENT OF TIME EXCEEDED					
		94 GHz			60 GHz		
		1%	5%	50%	1%	5%	50%
ALL	90	55	23	1	159	134	125
20,000	60.68	63	27	1	183	154	143
10,000	60.26	63	27	1	184	154	144
5,000	59.35	64	27	1	185	156	145
2,000	58.15	65	28	1	188	158	147
1,000	56.25	66	28	1	192	161	149
500	54.46	67	29	1	196	165	153
200	52.09	69	30	1	202	170	158
100	50.69	71	30	1	206	173	161

Table 10. Total One-way Atmospheric Attenuation (dB) for Southern Florida During July.

HEIGHTS NM	ELEV ANGLE	PERCENT OF TIME EXCEEDED					
		94 GHz			60 GHz		
		1%	5%	50%	1%	5%	50%
ALL	90	46	25	2	140	133	124
20,000	60.68	53	28	2	166	153	142
10,000	60.26	53	29	2	167	154	143
5,000	59.35	54	29	2	169	155	144
2,000	58.15	54	29	2	171	157	146
1,000	56.25	56	30	2	174	160	149
500	54.46	57	30	2	178	164	152
200	52.09	59	31	2	184	169	157
100	50.69	60	32	2	187	172	160